New Convex Grating Types Manufactured by Electron Beam Lithography

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Abstract

High-performance blazed gratings have been fabricated on convex surfaces by electron beam lithography, for use in an instrument to be flown on NASA's NM-EO1 spacecraft.

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The advantages of spectrometer forms utilizing concentric surfaces have been recognized for some time.[1,2] In order to realize these advantages in practice, a reliable and flexible method of generating gratings on curved substrates is needed. Concave gratings are commonly manufactured using both ruling and holographic techniques. However, it is difficult to produce well-blazed curved gratings.[3,4,5] These difficulties are exacerbated in concentric spectrometer designs in which the grating must typically cover an arc that is greater than the blaze angle itself.

Using electron-beam (E-beam) lithography techniques[6,7,8] it has been possible to manufacture a variety of convex gratings that are admirably suited to the requirements of concentric spectrometers and in fact enable the practical realization of these designs. The motivation for this work was provided by the New Millennium Earth Orbiting 1 mission, which is scheduled to test a grating-based imaging spectrometer from low Earth orbit. One of the gratings described here has been selected for the above mission. The gratings were meant to cover simultaneously two wavelength regions, 1-2.5 μm in the first order, and 0.4-1 μm in the second order.

The grating designs that have been produced and tested are the following:

1) true blazed gratings, in which the blaze angle remains constant relative to the local surface normal
2) dual-panel blazed gratings, which split the total grating area into two (concentric) regions with different blaze angles, thus providing a broader wavelength band, and
3) dual-angle blazed gratings, which incorporate a groove with a compound profile having two segments with different slopes. This also has the effect of broadening the wavelength response band, especially in the second order.

The E-beam method provides great flexibility in designing the groove shape and blaze angle, including any desirable variations (or lack thereof) across the grating. In addition, it permits arbitrary panel shape for a multi-panel grating as well as control of the average diffracted phase form each panel. All these characteristics are important in determining the image quality of an imaging spectrometer.

The method involves first coating the flat or low sphericity substrate with a thin (2 – 3 μm) film of polymethyl methacrylate (PMMA, Plexiglas) using a standard semiconductor fabrication spin-coater. The grating pattern is written by an electron beam lithography tool using, typically, a 50 kV, 2 mA, 0.5 μm waist beam. In order to produce flat, blazed surfaces, it is necessary to compensate for both (a) the nonlinear response of the PMMA and (b) the E-beam 'proximity effect', exposure produced by electrons that are back-scattered from deep within the substrate. This is accomplished by (a) careful calibration and (b) deconvolution of the experimentally determined, delta plus Gaussian instrument function. The exposed patterns are developed in pure acetone for roughly 10 seconds. Final grove depth is adjusted to the design value using incremental development steps interspersed with physical depth measurements. When working with curved substrates, the pattern is subdivided into narrow annular regions that can be exposed adequately at fixed E-beam focal distance. Coincident with changing the focal distance, the E-beam electronic deflector circuits must be adjusted both for scale and rotation. Again careful calibration is necessary. It is found that adequate precision can be realized over a region that varies ±25 μm in height. Fig. 1 illustrates the quality of gratings that have been produced using these techniques. It shows atomic force microscope (AFM) data that includes the boundary between zones having different blaze angles. A fine (sub micron) 'picket fence' of residual PMMA separates the regions. It is the result of imperfect pattern matching and/or exposure. Fig. 2 illustrates an actual part.

Fig. 3 shows the relative diffraction efficiency of four different gratings with similar specifications, all produced on the same convex substrate. The efficiency up to 1 μm is that of the second order; above, that of the first order. It can be seen that the highest peak efficiency is provided by the dual-angle blazed grating, while the dual-blaze grating gives the best overall efficiency within the bands of interest. A similar broadband response is obtained by the ruled grating (which was a 3-panel design), due to the variation in blaze angle that is inevitable with this type. The holographic grating was not an enhanced (ion-etched) type and had limited maximum attainable efficiency.

Compared to the ruled and holographic gratings, E-beam gratings exhibited extremely low scatter. Using a HeNe laser and a 100 µm slit in front of a photodetector, scatter from the E-beam grating was not measurable while that from both the ruled and the holographic gratings was clearly measurable. Regular ghosts at ¼ of the spacing between orders were observed, with a maximum intensity of 0.2% relative to the second order at 632.8nm. However, even this value compared favorably with the satellites or scatter generated by the conventional gratings.

The wavefront quality of the E-beam gratings was also superior. For the single blaze or dual-angle blaze gratings, a p-v wavefront error of 0.2λ was observed at 632.8nm. This was comparable with the wavefront quality of the holographic grating. The dual blaze gratings presented a discontinuity at the blaze boundary, which was due to experimental error in matching the average heights of the two blaze areas (a maximum of $\lambda/5$ at 632.8nm). However this was only half the value obtained for the ruled grating. A second dual blaze grating showed a better match between blaze areas ($\lambda/10$).

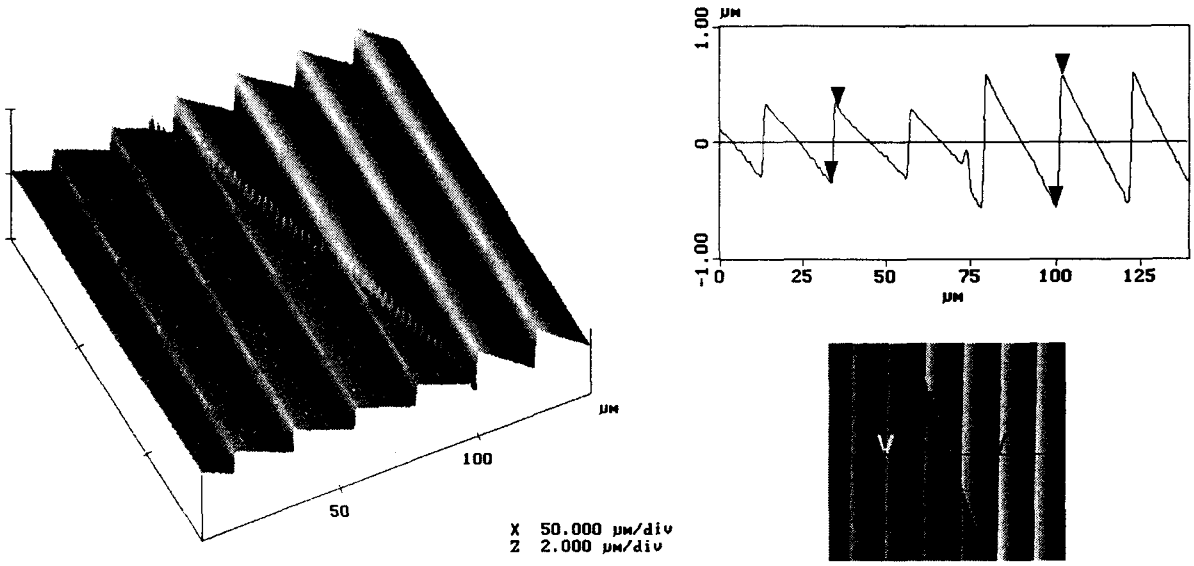

Figure 1. Atomic force microscope surface profile of a dual-blaze grating on a convex substrate.

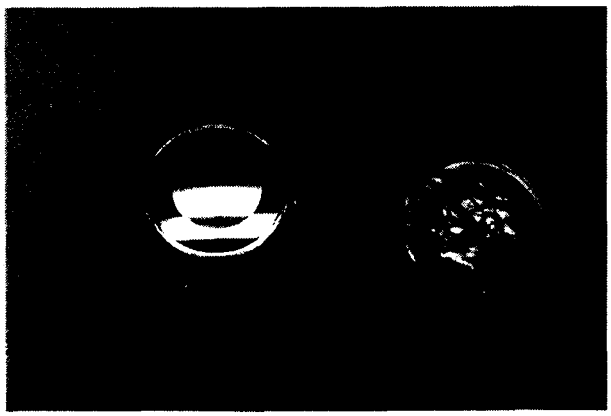

Figure 2. Photograph of a single-blaze convex grating on a flight substrate. Note the shift of the reflected image due to the high visible-wavelength efficiency of the second order.

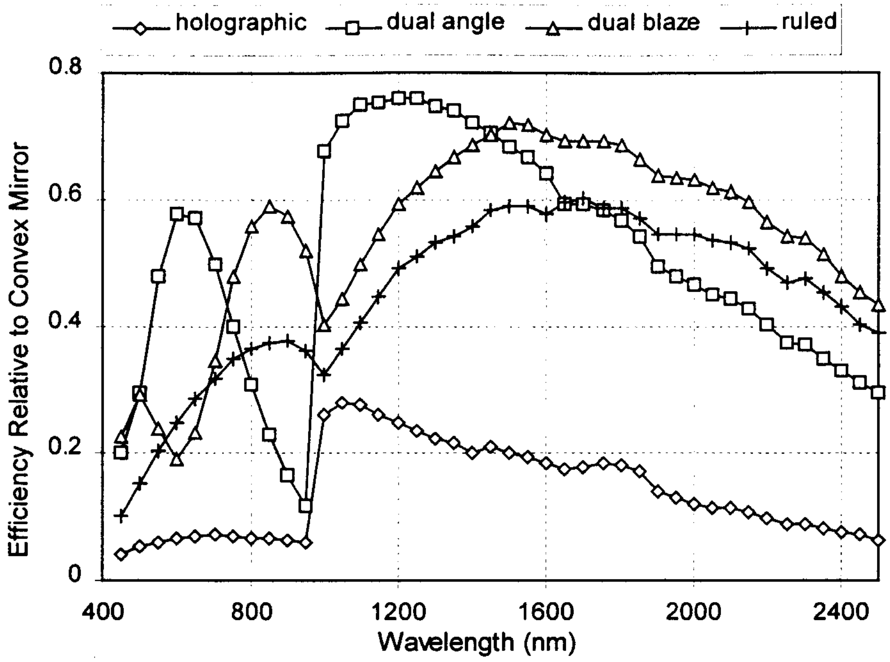

Figure 3. Efficiencies of two E-beam fabricated gratings (dual angle and dual blaze), a holographic grating, and a ruled grating. 400-1000 nm: second order efficiency, 1000-2500 nm: first order efficiency

The flight candidate gratings were subjected to environmental tests, including thermal cycling (-50 to +50° C), vibration, out-gassing, and tape-test adhesion on witness samples. All tests were successful and no variation in optical properties was detected.

In conclusion, electron-beam lithography has been shown to be capable of producing high-quality gratings on convex substrates that compare favorably with gratings produced through conventional techniques. The method allows great flexibility in grating design and thus enables the practical realization of new spectrometer design forms.

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